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(54) **Random access in multicarrier systems**

(57) Utilisation of frequency divided OFDM (FD OFDM) in the uplink of a multi-access system requires that all mobile stations meet the requirements for orthogonality between sub-carriers in the time and frequency domain. Alternatively, another access technique can be used with OFDM, which can tolerate some relaxation in orthogonality requirements, e.g. code division OFDM (CD OFDM, or COFDM). The use of FD OFDM thus requires a random access technique that does not disturb the orthogonality between sub-carriers. Because time synchronisation is essential if orthogonality is to be preserved between sub-carriers, it is vital that delay difference between a mobile station and a base station be estimated during a random access protocol.

In a random access protocol, a mobile station transmits a known signal sequence to a base station. The base station can lock onto the known sequence, detect it and estimate the time delay. According to the present invention, the random access sequence can be repeated cyclically and may comprise a m-sequence, a Gold sequence, or a four phase sequence with good cross-correlation properties, which is modulated onto the sub-carriers in the frequency domain. The random access sequence is transmitted without guard spaces. The random access sequence may be modulated onto all sub-carriers, or alternatively onto selected sub-carriers only. Alternatively, the random access sequence may be modulated onto all sub-carriers, but some sub-carriers may be transmitted at higher power than others.

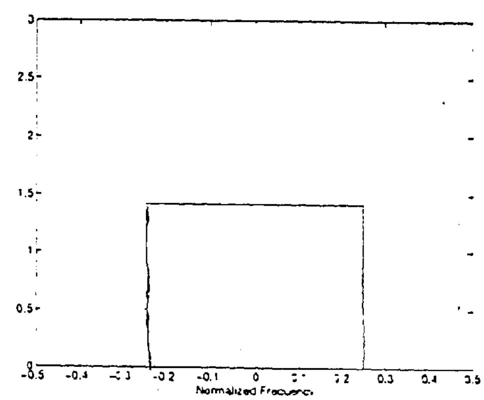

Fig 1

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Description

The present invention relates to the use of OFDM (orthogonal frequency division multiplex) in radio telephony systems, more particularly to a random access protocol, i.e. to the manner in which a mobile station (MS) in a radio telephony system initiates a call, or the manner in which a call is handed over from one base station (BS) to another (handover).

A random access (RA) protocol is the method by which a mobile station initiates contact with a base station, when the base station is not synchronised with the mobile station. This situation can arise when a mobile station initiates a call, i.e. is activated, or when a call in progress is transferred from one base station to another base station.

In an OFDM system, data is modulated onto a broadband signal comprising a large number of individual frequency carriers which form a frequency division multiplex. The bandwidths of the individual sub-carriers, are small and arranged so that the maximum of the sinc(x), (sinc(x) = sin(x)/x), power spectrum, of one carrier, corresponds with the first minimum in the sinc(x) power spectrum of the adjacent carrier. In other words, the carrier separation equals 1/(symbol length), for rectangular symbols. It is for this reason that adjacent carriers are described as "orthogonal". OFDM systems normally use a FFT (fast fourier transform) process to demodulate the data signal from the transmitted signal. Convolution error coding and FFT may be employed at the modulator (transmitter) stage. In the receiver, complementary FFT processing is combined with Viterbi decoding, at the demodulator stage. This ensures that the overall bit error rate is very low. This particular variant of OFDM is known as CD OFDM (Code Division Orthogonal Frequency Division Multiplex). For convenience, in this specification the term OFDM is used to refer to both FD OFDM and CD OFDM, unless specific reference is made to either FD OFDM, or CD OFDM.

Utilisation of frequency divided OFDM (FD OFDM) in the uplink of a multi-access system requires that all mobile stations meet the requirements for orthogonality between sub-carriers in the time and frequency domain. The use of FD OFDM thus requires a random access technique that does not disturb the orthogonality between sub-carriers. Because time synchronisation is essential, if orthogonality is to be preserved between sub-carriers, it is vital that the delay difference between a mobile station and a base station be estimated during a random access protocol.

In a random access protocol, a mobile station transmits a known signal sequence to a base station. The base station can lock onto the known sequence, detect it and estimate the time delay. According to the present invention, the random access sequence can be repeated cyclically and may comprise a m-sequence, a Gold sequence, or a four phase sequence with good cross-correlation properties, which is modulated onto the sub-carriers in the frequency domain. The random access sequence is transmitted without guard spaces. The random access sequence may be modulated onto all sub-carriers, or alternatively onto selected sub-carriers only. Alternatively, the random access sequence may be modulated onto all sub-carriers, but some sub-carriers may be transmitted at higher power than others.

Multi-access radio telephony systems are of course well known, e.g. the GSM system, in which a plurality of mobile stations are served via a plurality of base stations connected to a communications infrastructure for controlling individual communications and routing such communications via a land based network, e.g. a PSTN. All such systems require a random access protocol, or procedure. The use of OFDM for such systems is also known. However, the requirements of OFDM with regard to sub-carrier orthogonality imposes special problems. The present invention proposes a solution to these problems.

PCT patent application WO 95/07581 describes a method of synchronising an OFDM QAM, or QPSK, receiver when it is first switched on. The signal power is set at zero for part of the synchronisation symbol. During the remaining part of the symbol, the symbol is modulated with a sequence that has optimum autocorrelation properties. The invention is alleged to require only a single symbol for synchronisation.

US Patent 5,228,025 discloses a method of synchronisation for use in an OFDM system. Certain sub-carriers are omitted, or reduced in power, in the sub-carrier raster. The method is applied to the broadcasting of digital data in multiple channels, notably radio (programme) broadcasting, and the synchronisation pattern is repeated.

PCT patent application WO 92/16063 discloses an OFDM system for broadcasting and receiving digital data within time division multiplexed channels. Each OFDM frame includes frequency reference symbols for synchronisation of a receiver with a transmitter.

Synchronisation techniques used in OFDM and TDMA systems are also disclosed in the following documents: US Patent 5,191,576; PCT patent application WO 93/11616; European patent application 0,549,445 A1; and European patent application 0,608,024 A1.

None of the cited prior art documents disclose the use, in a digital radio telephony system, of a random access protocol in which a random access sequence can be cyclically repeated, to facilitate connection of a mobile station to a base station on call initiation, or call handover.

According to a first aspect of the present invention, there is provided a random access protocol for use in a multi-access digital radio communications system having a plurality of mobile stations and a plurality of base stations and using OFDM for an uplink between a mobile station and base station in which a mobile station transmits a random access sequence, characterised in that said mobile station cyclically repeats said random access sequence.

Preferably said uplink employs FD OFDM.

Preferably said mobile station listens for a PICH transmitted by said base station, and after detection of said PICH, said mobile station synchronises to OFDM symbols transmitted by said base station, said mobile station listens to a BCH for a random access sequence and a subcarrier number assigned to an AGCH and then transmits said random access sequence in a random access channel and, after transmission of a plurality of cycles of said random access sequence, said mobile station checks the AGCH to determine whether, or not, said base station has granted said mobile station access.

Preferably said random access sequence is transmitted at a power determined by data carried on the AGCH channel and, if said mobile station is not granted access to said base station, said mobile station retransmits said random access sequence at higher power.

Preferably, on detection of said random access sequence, said base station raises a busy flag in said BCH by removing the random access sequence from said BCH, said base station transmits timing advance information on the AGCH, said mobile station adjusts its timing advance in accordance with said transmitted data, and said mobile station transmits another random access with a new random access sequence to verify timing advance adjustment by said mobile station.

Preferably, on receipt of said new random access sequence, said base station transmits an acknowledgment on said AGCH together with data informing said mobile station which sub-carriers will be employed for a DICH and DCCH, and said mobile station then transmits a randomly selected number which is echoed by the base station, to identify the mobile station, in order to prevent data collisions.

Said random access sequence may be a m-sequence.

Alternatively said random access sequence may be a Gold sequence.

Alternatively said random access sequence may be a four phase sequence with good cross-correlation properties.

Said random access sequence may be applied to all available sub-carriers.

Alternatively certain sub-carriers, dedicated to said random access channel, to which said random access sequence is applied, may be transmitted at a higher power than other sub-carriers, to which said random access sequence is also applied.

Alternatively said random access sequence may be applied only to certain sub-carriers dedicated to said random access channel.

Sub-carriers dedicated to said random access channel may be unequally spaced from each other.

Said random access sequence may be cyclically repeated without any guard space between symbols, all other channels bearing modulated data, such as, BCH and DICH, may include guard spaces between symbols.

Said guard spaces may have a duration which has an integer relationship to the duration of a symbol in said random access channel.

A base station may respond to a random access sequence transmitted by a mobile station if, and only if, said random access sequence is detected in at least two consecutive data frames.

According to a second aspect of the present invention, there is provided a mobile radio telecommunications system comprising a plurality of base stations, a plurality of mobile stations and using OFDM for uplinks between mobile stations and base stations, characterised in that said mobile radio telecommunications system is adapted to operate with a random access protocol as set out in the preceding paragraphs.

According to a third aspect of the present invention there is provided a method of measuring performance of a random access sequence, suitable for use with a random access protocol as set out above, characterised in that a signal is generated by modulating a random access sequence to be tested onto a plurality of sub-carriers and then subjecting said signal to IFFT processing, introducing a time shift into said signal, subjecting said signal to a multi path model processing to simulate delay spread and doppler shift and passing said signal to a receiver in which said random access sequence is detected and timing advance estimated.

Noise may be injected into said signal, after said signal has been subject to said multi path model processing.

According to a fourth aspect of the present invention there is provided apparatus for measuring performance of a random access sequence, suitable for use with a random access protocol as set out above, characterised in that said apparatus includes IFFT means for inverse fourier transform processing of a signal comprising a random access sequence to be tested, said signal being modulated onto a plurality of sub-carriers; time shift means for introducing a random time shift, with a uniform distribution over the duration of one symbol, into the signal; modelling means for simulating, on said signal, the effects of delay spread and doppler shift; and receiving means for detecting said random access sequence and estimating timing advance.

Noise generating means may be provided for injecting noise into said signal, after said signal has passed through said modelling means.

According to a fifth aspect of the present invention there is provided a mobile radio telecommunications system comprising a plurality of base stations and a plurality of mobile stations and using FD OFDM for uplinks between mobile stations and base stations, and employing a random access protocol in which a mobile station transmits a random

access sequence, characterised in that:

- said mobile station listens for a PICH transmitted by said base station;
- after detection of said PICH, said mobile station synchronises to OFDM symbols transmitted by said base station, said mobile station then transmits said random access sequence in a random access channel;
- said mobile station listens to a BCH for a random access sequence that is free and a subcarrier number for an AGCH;
- after transmission of a plurality of cycles of said random access sequence, said mobile station checks an AGCH to determine whether, or not, said base station has granted said mobile station access;
- said random access sequence is transmitted at a power determined by data carried on the AGCH channel;
- if said mobile station is not granted access to said base station, said mobile station retransmits said random access sequence at higher power;
- on detection of said random access sequence, said base station raises a busy flag in the BCH by removing said random access sequence from said BCH;
- said base station transmits timing advance information on the AGCH;
- said mobile station adjusts its timing advance in accordance with said transmitted data;
- said mobile station transmits another random access with a new random access sequence to verify timing advance adjustment by said mobile station;
- on receipt of said new random access sequence, said base station transmits an acknowledgment on said AGCH together with data informing said mobile station which sub-carriers will be employed for a DICH and DCCH;
- said mobile station then transmits a randomly selected number which is echoed by the base station to identify the mobile station in order to prevent data collisions; and
- said mobile station cyclically repeats said random access sequence.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates the power spectrum of a first type of random access channel.

Figure 2 illustrates the power spectrum of a second type of random access channel.

Figure 3 illustrates the impulse response of a matched filter for an m-sequence length of 511.

Figure 4 illustrates the impulse response of a matched filter for an m-sequence of 31 padded with zeros to a length of 511, with dedicated sub-carriers being unequally spaced.

Figure 5 illustrates the impulse response of a matched filter for an m-sequence of 31 padded with zeros to a length of 511, with dedicated sub-carriers being equidistant.

Figure 6 illustrates the relationship between the information channel (DICH) and the random access channel.

Figure 7 illustrates an arrangement for environmental simulation of an OFDM system to which the present invention relates.

Figure 8 illustrates a noise spectral density for punctuated noise.

Figure 9 illustrates a random access channel used for simulation.

Figure 10 illustrates the effects of random access channel type on a performance score.

Figure 11 illustrates the influence of channel frequency response on a random access channel.

Figures 12 and 13 illustrate the performance of a random access protocol, according to the present invention.

Figures 14 and 15 illustrate the probability of a mobile station breaking orthogonality, using a random access protocol, according to the present invention.

A large number of abbreviations are used in the description of embodiments of the present invention. To assist the reader, a glossary of the principle terms and abbreviations employed in this patent specification is set out below.

ACA: Adaptive Channel Allocation

AGCH: Access Grant Channel

BCH: Broadcast Control Channel, sometimes abbreviated as BCCH

BS: Base Station

C-time: Correlation time

CD-OFDM: Code Division OFDM

COFDM: Coded OFDM

CODIT: Code Divided Testbed - subject of a Race II project

DCCH: Dedicated Control Channel

DICH: Dedicated Information Channel

FD-OFDM: Frequency Division OFDM

FFT: Fast Fourier Transform

Gold code: Pseudo-random sequence defined by R. Gold in 1967 with low mutual cross-correlation

GSM: A European standard for digital mobile cellular radio telephony.

IFFT: Inverse Fast Fourier Transform

m-sequence: Maximum Length Sequence

MS: Mobile Station

OFDM: Orthogonal Frequency Division Multiplex

PICH: Pilot Channel

PSTN: Public Switched Telephone Network

QAM: Quadrature Amplitude Modulation

QPSK: Quadrature Phase Shift Keying

RA: Random Access

RACH: Random Access Channel

SCH: Synchronisation Channel

SNR: Signal to Noise Ratio

TA: Timing Advance

TDMA: Time Division Multiple Access

U/I: User to Interference Ratio

A random access protocol, according to the present invention, will now be described, with reference to call set up. A similar procedure may, of course, be used in call handover between base stations. Initially, a mobile station listens for the PICH transmitted by the base station. The PICH provides the base station identification and, in combination with the SCH, enables the mobile station to synchronise to OFDM symbols transmitted by the base station. The mobile station must then synchronise with the BCH so that it can obtain information about which random access sequence to use and which sub-carriers will be utilised by the AGCH. The mobile station then transmits the random access sequence and increases the output power in accordance with power control information transmitted by the base station over the AGCH. The mobile station transmits 25 consecutive random access sequences, checks the AGCH to see if random access has been granted, and, if not, increases the output power and tries again. The initial output power on the random access channel is based on the received power from the base station, together with some margin. The duration of 25 consecutive random access sequences is 5 ms.

When the base station detects the random access channel, a busy flag is raised on the BCH by removing the random access code from the BCH. The base station sends timing advance information on the AGCH. The mobile station then adjusts the time offset in accordance with the TA information and transmits a new random access sequence to verify the adjusted time offset. The base station sends an acknowledgement on the AGCH if the correct TA information was used. The base station informs the mobile station which sub-carriers the mobile station should utilise for the DICH and corresponding DCCH. The mobile station then transmits a randomly selected number, which is echoed by the base station, and is used to identify the mobile station and resolve any possible collision problems.

Three different types of random access channel protocol may be used. All of these, may be based on a m-sequence, mapped on the sub-carriers in the frequency domain. Each sub-carrier transfers a four-phase constellation (QPSK). The same m-sequences are used to form the I and Q components of the OFDM signal, (the I component is the in-phase component and the Q component is the quadrature phase component). The good autocorrelation properties of m-sequences make them suitable for use in random access protocols. Other possible sequences are Gold sequences, or four-phase sequences with good cross-correlation properties. In fact, there may be advantages in using the latter two sequences in certain systems.

The three types of random access channel are herein denoted as type 1, type 2 and type 3.

A type 1 random access channel carries the random access sequence on all available sub-carriers. The m-sequence has a length of 511 symbols. This type of random access channel operates at very low SNR so that the random access doesn't disturb other traffic.

A type 2 random access channel is similar to type 1 random access channel in that the m-sequence is placed on all sub-carriers. However, some of the sub-carriers are dedicated to the random access channel, are not available to other users, and use a higher power.

A type 3 random access channel uses only dedicated sub-carriers for the random access sequence. As in type 2 random access channel, dedicated sub-carriers are not available to other users, so the SNR will be significantly better. The m-sequence will, however, be much shorter because only a limited number of sub-carriers are allocated to the random access channel.

The spectra of type 1 and type 2 random access channels are shown in Figures 1 and 2 respectively. Spreading of the random access sequence over all sub-carriers, in type 1 and type 2 random access channels, facilitates the estimation of the offset time of a known sequence which is drowned in noise. The type and length of the sequence is a determining factor for the SNR. Because the random access channel will interpret other users' information as noise, and vice versa, the power ratio between users and the random access channel should be as large as possible so that the random access channel does not interfere with normal traffic.

The spacing, between random access channel dedicated sub-carriers, is critical to the performance of time offset estimation. The effect of sub-carrier choice for the random access channel, on time offset estimation, is illustrated in Figures 3 to 5. Figure 3 corresponds to a full length, 511, m-sequence, while Figures 4 and 5 correspond to a m-sequence of length 31 with zeros padding the length to 511. In Figure 4, the sub-carrier spacing, between sub-carriers dedicated to the random access channel, varies, while in Figure 5, the sub-carrier spacing, between sub-carriers dedicated to the random access channel, is the same, i.e. dedicated sub-carriers are evenly distributed throughout the OFDM raster. When the dedicated sub-carriers are equally spaced, an ambiguity occurs with the time offset, as can be seen from Figure 5. The choice of an appropriate separation between the sub-carriers, dedicated to the random access channel, minimises this ambiguity, as can be seen from Figure 4.

Before the random access sequence is subjected to IFFT in the transmitter, zeros are padded into the sequence to generate a 1024 point array. This band limits the random access channel, see Figures 1 and 2. The random access sequence is repeated cyclically without any guard space. All other channels, e.g. BCH and DICH, that carry modulated information, include a guard space between symbols, see Figure 6. An advantageous property of the cyclically repeated, band limited, random access sequence is that orthogonality is maintained and it is, therefore, easy to estimate the time offset required by the delay difference. The relationship between the duration of the random access channel and the duration of the guard time should be an integer, N, so that the random access channel will be synchronised to all

other channels each Nth OFDM symbol, see Figure 6, i.e. an integer relationship exists between the duration of a guard space and the duration of an OFDM symbol in the random access channel.

Two important parameters for judging the performance of a random access protocol are the probabilities for the occurrence of a false detection of a random access sequence and failure to detect a correct random access sequence. A random access sequence is said to have been detected when a base station correctly identifies that a mobile station has transmitted a random access sequence. A mobile station also has to measure the propagation delay in a received random access sequence, herein called estimation. Detection and estimation are performed in two separate arms of a receiver, see Figure 7.

A false alarm is defined as the detection of a random access sequence when no such sequence has been transmitted by a mobile station in the cell served by the base station. False alarms may be caused by:

- detection of a random access sequence transmitted by a mobile station in a neighbouring cell; or
- background noise being incorrectly interpreted as a random access sequence.

The first case above is considered to be unlikely, and the probability can be further reduced by requiring two random access attempts using different random access sequences.

In the second case, the probability of a false alarm, is the probability that white Gaussian noise be interpreted as a random access sequence. Based on the arrangement described with reference to Figure 7, the energy signal entering the detector can be written as:

$$E=\sum_{i=1}^{n}|X_{R,i}+j.X_{I,i}|^2$$
$$=\sum_{i=1}^{n}X_{R,i}^2+\sum_{i=1}^{n}X_{I,i}^2$$
$$=\sum_{i=1}^{2n}X_i^2$$

where $X_{R,i}$, $X_{I,i} \in N(0,\sigma)$, and are the real and imaginary parts of the noise in sub-carrier i, n is the number of sub-carriers dedicated to the random access channel, $N(0,\sigma)$ is white Gaussian noise with a zero mean and standard deviation σ. The last step is taken on the assumption that all noise is uncorrelated, $X_i \in N(0,\sigma)$. It can be shown that $E \in \chi^2$ with $m = 2n$ degrees of freedom, i.e. E has a Chi square distribution, see J.G. Proakis "Digital Communications" Mc Graw-Hill 2nd ed., 1989, which gives

$$E\{E\} = m.o^2 = 2.n.o^2$$

and in the case when m is even
where $F_E(y)$ is the probability of value y and F_E is the probability density function of E.

$$F_E(y)=1-e^{\frac{y}{2.\sigma^2}}.\sum_{k=0}^{n-1}\frac{1}{k!}.\left(\frac{y}{2.\sigma^2}\right)^k$$

The probability of a false alarm, P_{FA}, can now be calculated as

$$P_{FA} = P(E>K.E\{E\}) = 1 - P(E \geq K.2.n.\sigma^2)$$

$$=1-F_E(K.2.n.\sigma^2)$$

$$=e^{-K.n}.\sum_{k=0}^{n-1}\frac{1}{k!}.(K.n)^k$$

where K is the number of times the signal has to rise above the normal noise energy floor and k is the summation variable.

The probability of a false alarm for different values of K and n is set out in the following table:

	n=3	n=5	n=10	n=15	n=31
K=2	$9.15x10^{-2}$	$2.92x10^{-2}$	$499x10^{-3}$	$9.21x10^{-4}$	$4.99x10^{-6}$
K=3	$1.73x10^{-2}$	$8.57x10^{-4}$	$7.12x10^{-6}$	$6.57x10^{-8}$	$2,55x10^{-14}$

The use of K = 2 and 31 dedicated sub-carriers gives a false alarm probability of $4.99x10^{-6}$ which corresponds to one false alarm every 40 seconds (GSM allows a false alarm every 23 seconds). This probability could be drastically reduced if g successive frames must fulfil the detection criteria. If these events can be considered as independent, the false alarm rate is

$$P_{FA,g} = P_{FA}^{g}$$

The use of K = 2 and g = 2 would give a false alarm rate of $2.49x10^{-11}$ which corresponds to one false alarm every 13th week.

The probability of a correct random access is defined as the probability of detecting the random access and estimating the timing advance information. This probability is difficult to compute, so it must be evaluated using a simulation. Suppose that:

- A is the event of a correct detection; and
- B is the event of correct timing advance estimation.

The probability of one correct random access attempt can be expressed as

$$P_1(A \cap B) = P(A).P(B/A)$$

where the probabilities P(A) and P(BIA) are easy to measure in a simulation.

The signalling protocol demands two successive random access attempts. These two attempts may be assumed to be independent, even though the small time difference between the attempts implies that they are not independent. However, if the first random access attempt succeeds, it is likely that the next one will also succeed, because there will only be small changes in the channel. A worst case could then be considered as two independent attempts, which can be written as

$$P_{RA} = P_1(A \cap B).P_2(A \cap B) = (P(A \cap B))^2$$

A special problem occurs when the base station detects the random access but can't perform a correct timing advance estimation. In CODIT this is treated as a false alarm but this can't be done in the OFDM case because an error in timing advance information will lead to lost orthogonality in the mobile station and this will jam other users. The solution resides in the signalling protocol, (the random access protocol), previously described, which requires an additional random access to be transmitted to check the timing advance estimation. This will not break the orthogonality. The probability of jamming can then be calculated as the probability of two (independent) successive random access

attempts where detection is successful but estimation fails. All other cases do not lead to a loss of orthogonality, because no transmission is permitted from the mobile station. Using the same variables as before, this probability can be written as

$$P_J = P(A_1 \cap \bar{B}_1)) . P(A_2 \cap \bar{B}_2) . P_{equal}$$

where $\bar{B}_X$ is the complementary event in random access number x and P_{equal} is the probability of two successive estimations differing by no more than half a guard space in each direction, which seems to be a reasonable tolerance. The value of P_{equal} is difficult to calculate, or estimate. If it is assumed that there is uniform distribution of the estimations and that the guard space is approximately 10% of the OFDM frame, then $P_{equal} = 0.10$, the last equation can then be rewritten as

$$P_J = (P(A) - P(A \cap B))^2 . P_{equal}$$

where $P(A \cap B)$ is the probability of one correct random access attempt.

The performance of different random access protocols can be measured using the apparatus illustrated in Figure 7. This apparatus simulates a fast fading mobile radio channel, which corresponds to a macro cell environment. The delay spread is approximately 10% of the C-time and maximum doppler spread is chosen to be about 2% of the sub-carrier bandwidth. The random access sequence is allocated to sub-carriers, in accordance with the random access protocol under test, to form a signal which is subjected to IFFT. A time shift is then introduced into the signal to simulate the propagation delay between the mobile station and base station. A random time shift with a uniform distribution over the duration of one OFDM symbol is used during each random access attempt. Delay spread and doppler shift are simulated using a 100-tap multi-path model corresponding to a Jakes model, see W. C. Jakes et al., "Microwave Mobile Communications", John Wiley & Sons, New York 1974. Finally noise is added to the signal.

The noise used in the simulation is called punctuated noise. It consists of two complex components defined by two parameters, U/I and SNR. The spectral density of punctuated noise is illustrated in Figure 8. It should be noted that the parameters SNR and U/I are not the power spectral density, but parameters used to calculate the spectral density. It will be observed that there is a background noise level defined by SNR and a noise level representative of noise generated by other users of the system defined by U/I. The punctuation feature of the noise spectrum appears only when a subset of the available carriers are dedicated to the random access channel, as is the case with type 2 and type 3 random access channels. Other users will not use dedicated sub-carriers, so that the only noise appearing on these sub-carriers will be background noise. If it is assumed that there are a large number of users on the system, U/I noise can be approximated by complex Gaussian noise. During simulations, a normal traffic load is used and other users are assumed to occupy 37% of the sub-carriers, selected at random.

The receiver, illustrated in Figure 7, has two arms, one for time estimation and the other for random access detection.

The timing advance estimator uses a matched filter implemented in the frequency domain. To reduce the noise interference, an integrator is used to integrate over a number of random access frames. Typically, the integration may be performed over 24 OFDM symbols. This corresponds to a time period of between 2.5 ms and 5 ms, with a C-time duration between 100μs and 200μs, which represents a reasonable integration time in a mobile channel, see R Braun & U Dersh, "A Physical Mobile Radio Channel Model" IEEE Transactions Vehicular Technology, Vol 40, No 2, May 1991, pp 472 - 482.

The detection arm of the receiver picks out the sub-carriers dedicated to the random access channel and calculates total energy. The random access channel will be detected if the energy rises above the normal energy floor on K occasions. The next 25 energy values are saved, since the random access will end some where in this window. The last frame that meets the detection criteria is used for timing advance estimation. This procedure ensures that timing estimation is performed on a frame at the end of the random access procedure, when noise has been decreased by integration.

In assessing the performance of different random access protocols, key parameters are probability of detection, timing advance estimation and false alarm ratio.

The connection between dedicated sub-carrier distribution and performance is by no means simple. For type 2 and 3 random access channels, several simulations must be performed in order to determine a good pattern for the dedicated sub-carriers. To compare the different patterns, a score system can be used in which the score is defined as the highest peak in the impulse response divided by the second highest peak. The total energy in the random access channels must be maintained at the same level so that scores between different random access channels can be legitimately compared.

Figure 11 illustrates the effect of the number of sub-carriers on the score. It will be seen that random access channel type 2 always out performs random access channel type 3, because of the longer m-sequence employed in type 2 random access channel. For large numbers of dedicated, (to the random access channel), sub-carriers, there is little difference between the performance of type 2 and type 3 random access channels. Of course, when 511 dedicated sub-carriers are used, both type 2 and type 3 random access channels converge into type 1 random access channel.

Another problem, that is encountered with selection of a pattern of dedicated sub-carriers for type 2 and type 3 random access channels appears if a lot of information is concentrated into a narrow frequency band. If there is a dip in the channel frequency response in such a band, it will lead to a very substantial loss of information in the random access channel which will in turn make detection and estimation impossible. This problem only occurs in connection with a type 3 random access channel, and is illustrated in Figure 10. It is thus, important with a type 3 random access channel, to select a pattern of sub-carriers spread across the available OFDM frequency raster.

When only a limited number of sub-carriers are selected, a type 2 random access channel performs significantly better than a type 3 random access channel. There is little difference between the performance of type 1 and type 2 random access channels. The injection of power in a type 2 random access channel increases detection probability, the base station only has to check the output of the matched filter when there is a significant increase in power on the dedicated sub-carriers.

There is no simple solution to the choice of the number of sub-carriers dedicated to the random access channel. It could be advantageous, see the description relating to false alarm probability, to use very few sub-carriers dedicated to the random access channel, in combination with some 'successive frames' demand. This will, however, make the timing advance estimation less accurate, because of ambiguity as to which frame to use in the estimate. On the other hand, a large number of dedicated sub-carriers occupies a lot of capacity both in terms of bandwidth and signalling information. The use of 31 sub-carriers seems to represent an acceptable compromise, when arranged in the subcarrier pattern illustrated in Figure 9.

Simulations, using the apparatus illustrated in Figure 7, have confirmed theoretical calculations of false alarm probabilities.

Performance of the random access protocol of the present invention is illustrated in Figures 12 and 13. Figure 13 shows that the random access protocol can operate at very low U/I. The low probabilities of U/I depends on problems in the timing estimation. The detection probability never falls below 99.3% in the simulation. Figure 12 shows that performance is very dependent on SNR. The simulation shows that drop at low SNR depends mainly on the detection process which is independent of U/I.

The probability of jamming occurring as a result of breaking orthogonality, is illustrated in Figures 14 and 15.

Simulations performed on type 1, type 2 and type 3 random access channels show that a type 2 random access channel represents a particularly advantageous protocol, enabling easy detection and estimation of time delay between a mobile station and a base station without disturbing orthogonality.

The performance of a type 3 random access channel can be improved by using an equaliser that is implemented in the frequency domain.

Claims

1. A random access protocol for use in a multi-access digital radio communications system having a plurality of mobile stations and a plurality of base stations and using OFDM for an uplink between a mobile station and base station in which a mobile station transmits a random access sequence, characterised in that said mobile station cyclically repeats said random access sequence.

2. A random access protocol as claimed in claim 1, characterised in that said uplink employs FD OFDM.

3. A random access protocol as claimed in claim 2, characterised in that said mobile station listens for a PICH transmitted by said base station, and after detection of said PICH, said mobile station synchronises to OFDM symbols transmitted by said base station, said mobile station listens to a BCH for a random access sequence and a sub-carrier number for an AGCH and then transmits said random access sequence in a random access channel and, after transmission of a plurality of cycles of said random access sequence, said mobile station checks said AGCH to determine whether, or not, said base station has granted said mobile station access.

4. A random access protocol as claimed in claim 3, characterised in that said random access sequence is transmitted at a power determined by data carried on the AGCH channel and in that if said mobile station is not granted access to said base station, said mobile station retransmits said random access sequence at higher power.

5. A random access protocol as claimed in either of claims 3, or 4, characterised in that, on detection of said random access sequence, said base station raises a busy flag in said BCH by removing said random access sequence from said BCH, in that said base station transmits timing advance information on the AGCH, in that said mobile station adjusts its timing advance in accordance with said transmitted data, and in that said mobile station transmits another random access with a new random access sequence to verify timing advance adjustment by said mobile station.

6. A random access protocol as claimed in claim 5, characterised in that, on receipt of said new random access sequence, said base station transmits an acknowledgment on said AGCH together with data informing said mobile station which sub-carriers will be employed for a DICH and DCCH, and in that said mobile station then transmits a randomly selected number which is echoed by the base station, to identify the mobile station, in order to prevent data collisions.

7. A random access protocol as claimed in any previous claim, characterised in that said random access sequence is a m-sequence.

8. A random access protocol as claimed in any of claims 1 to 6, characterised in that said random access sequence is a Gold sequence.

9. A random access protocol as claimed in any of claims 1 to 6, characterised in that said random access sequence is a four phase sequence with good cross-correlation properties.

10. A random access protocol as claimed in any previous claim, characterised in that said random access sequence is applied to all available sub-carriers.

11. A random access protocol as claimed in claim 10, characterised in that certain sub-carriers, dedicated to said random access channel, to which said random access sequence is applied, are transmitted at a higher power than other sub-carriers, to which said random access sequence is also applied.

12. A random access protocol as claimed in any of claims 1 to 9, characterised in that said random access sequence is applied only to certain sub-carriers dedicated to said random access channel.

13. A random access protocol as claimed in either claims 11, or 12, characterised in that sub-carriers dedicated to said random access channel are unequally spaced from each other.

14. A random access protocol as claimed in any previous claim characterised in that said random access sequence is cyclically repeated without any guard space between symbols, and in that all other channels bearing modulated data, such as BCH and DICH, include guard spaces between symbols.

15. A random access protocol as claimed in claim 14, characterised in that said guard spaces have a duration which has an integer relationship to the duration of a symbol in said random access channel.

16. A random access protocol as claimed in any previous claim, characterised in that a base station responds to a random access sequence transmitted by a mobile station if, and only if, said random access sequence is detected in at least two consecutive data frames.

17. A mobile radio telecommunications system comprising a plurality of base stations, a plurality of mobile stations and using OFDM for uplinks between mobile stations and base stations, characterised in that said mobile radio telecommunications system is adapted to operate with a random access protocol as claimed in any of claims 1 to 16.

18. A method of measuring performance of a random access sequence, suitable for use with a random access protocol as claimed in any one claims 1 to 16, characterised in that a signal is generated by modulating a random access sequence to be tested onto a plurality of sub-carriers and then subjecting said signal to IFFT processing, introducing a time shift into said signal, subjecting said signal to a multi path model processing to simulate delay spread and doppler shift and passing said signal to a receiver in which said random access sequence is detected and timing advance estimated.

19. A method as claimed in claim 18, characterised in that noise is injected into said signal, after said signal has been

subject to said multi path model processing.

20. A method as claimed in claim 19, characterised in that said noise is punctuated noise.

21. Apparatus for measuring performance of a random access sequence, suitable for use with a random access protocol as claimed in any one claims 1 to 16, characterised in that said apparatus includes IFFT means for inverse fourier transform processing of a signal comprising a random access sequence to be tested, said signal modulated onto a plurality of sub-carriers; time shift means for introducing a random time shift, with a uniform distribution over the duration of one symbol, into the signal; modelling means for simulating, on said signal, the effects of delay spread and doppler shift; and receiving means for detecting said random access sequence and estimating timing advance.

22. Apparatus as claimed in claim 21, characterised in that said apparatus further includes noise generating means for injecting noise into said signal, after said signal has passed through said modelling means.

23. Apparatus as claimed in claim 22, characterised in that said noise generating means is adapted to generate punctuated noise.

24. A mobile radio telecommunications system comprising a plurality of base stations and a plurality of mobile stations and using FD OFDM for uplinks between mobile stations and base stations, and employing a random access protocol in which a mobile station transmits a random access sequence, characterised in that:

- said mobile station listens for a PICH transmitted by said base station;
- after detection of said PICH, said mobile station synchronises to OFDM symbols transmitted by said base station, said mobile station then transmits said random access sequence in a random access channel;
- said mobile station listens to a BCH for a random access sequence that is free and a subcarrier number for an AGCH;
- after transmission of a plurality of cycles of said random access sequence, said mobile station checks an AGCH to determine whether, or not, said base station has granted said mobile station access;
- said random access sequence is transmitted at a power determined by data carried on the AGCH channel;
- if said mobile station is not granted access to said base station, said mobile station retransmits said random access sequence at higher power;
- on detection of said random access sequence, said base station raises a busy flag in said BCH by removing said random access sequence from said BCH;
- said base station transmits timing advance information on the AGCH;
- said mobile station adjusts its timing advance in accordance with said transmitted data;
- said mobile station transmits another random access with a new random access sequence to verify timing advance adjustment by said mobile station;
- on receipt of said new random access sequence, said base station transmits an acknowledgment on said AGCH together with data informing said mobile station which sub-carriers will be employed for a DICH and DCCH;
- said mobile station then transmits a randomly selected number which is echoed by the base station to identify the mobile station in order to prevent data collisions; and
- said mobile station cyclically repeats said random access sequence.

25. A mobile radio telecommunications system as claimed in claim 24, characterised in that said random access se-

quence is a m-sequence.

26. A mobile radio telecommunications system as claimed in claim 24, characterised in that said random access sequence is a Gold sequence.

27. A mobile radio telecommunications system as claimed in claim 24, characterised in that said random access sequence is a four phase sequence with good cross-correlation properties.

28. A mobile radio telecommunications system as claimed in any of claims 24 to 27, characterised in that each of said plurality of mobile stations includes means adapted to apply said random access sequence to all available sub-carriers.

29. A mobile radio telecommunications system as claimed in claim 28, characterised in that certain sub-carriers are dedicated to said random access channel and in that each mobile station has power control means adapted to cause said certain sub-carriers to be transmitted at a higher power than other sub-carriers, to which said random access sequence is also applied.

30. A mobile radio telecommunications system as claimed in any of claims 24 to 27, characterised in that each mobile station includes means for applying said random access sequence to only certain sub-carriers, which are dedicated to said random access channel.

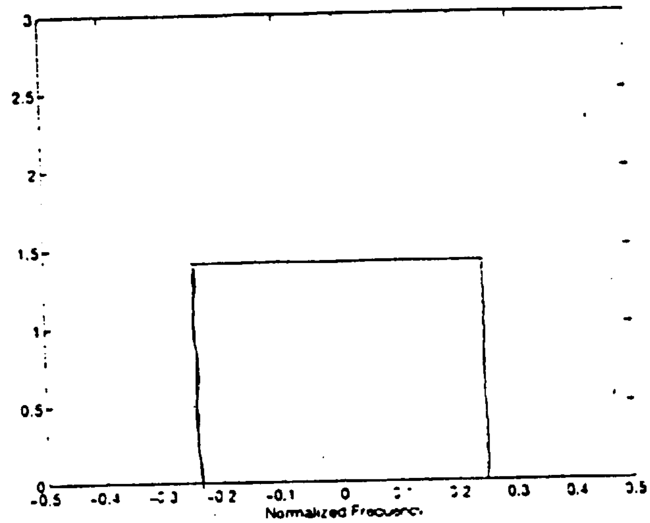


Fig 1

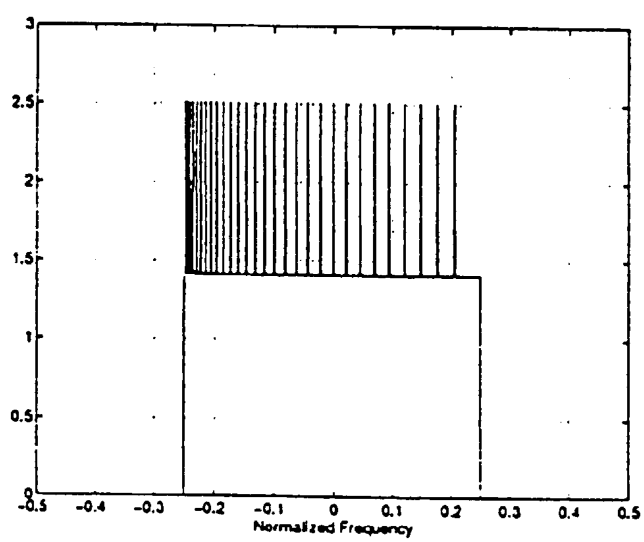


Fig 2

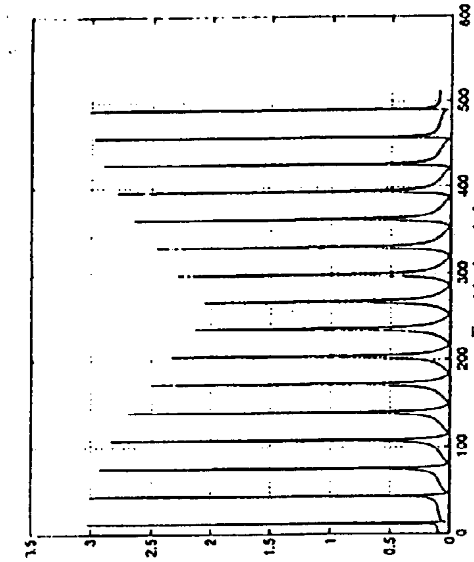


Fig 5

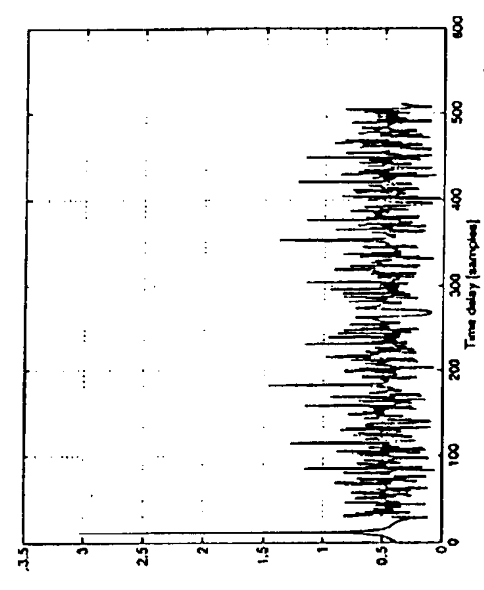


Fig 4

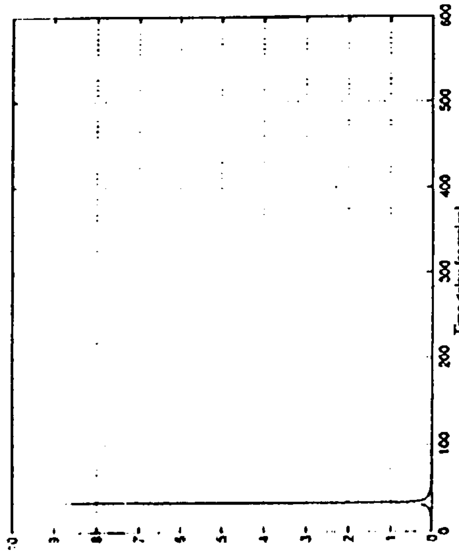


Fig 3

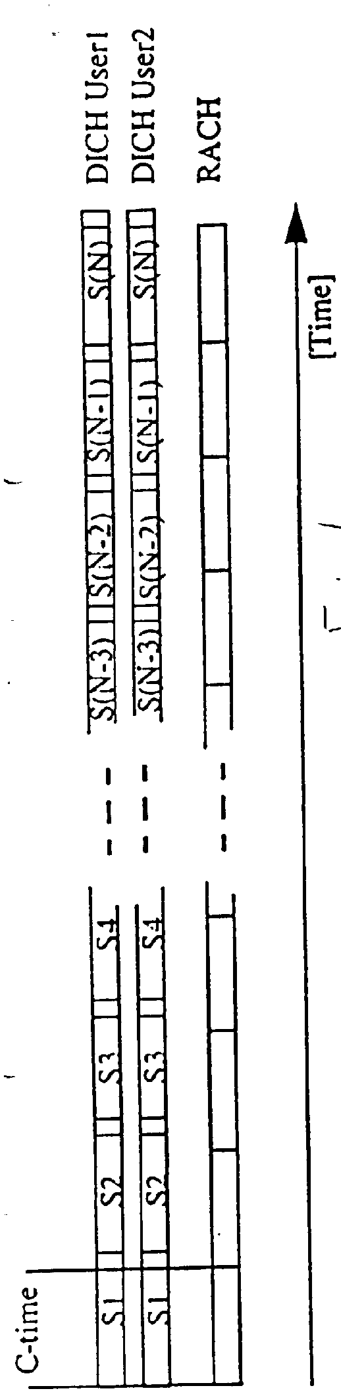

C-time
S1
S2
S3
S4
S(N-3)
S(N-2)
S(N-1)
S(N)
DICH User1
DICH User2
RACH
[Time]

Fig 6

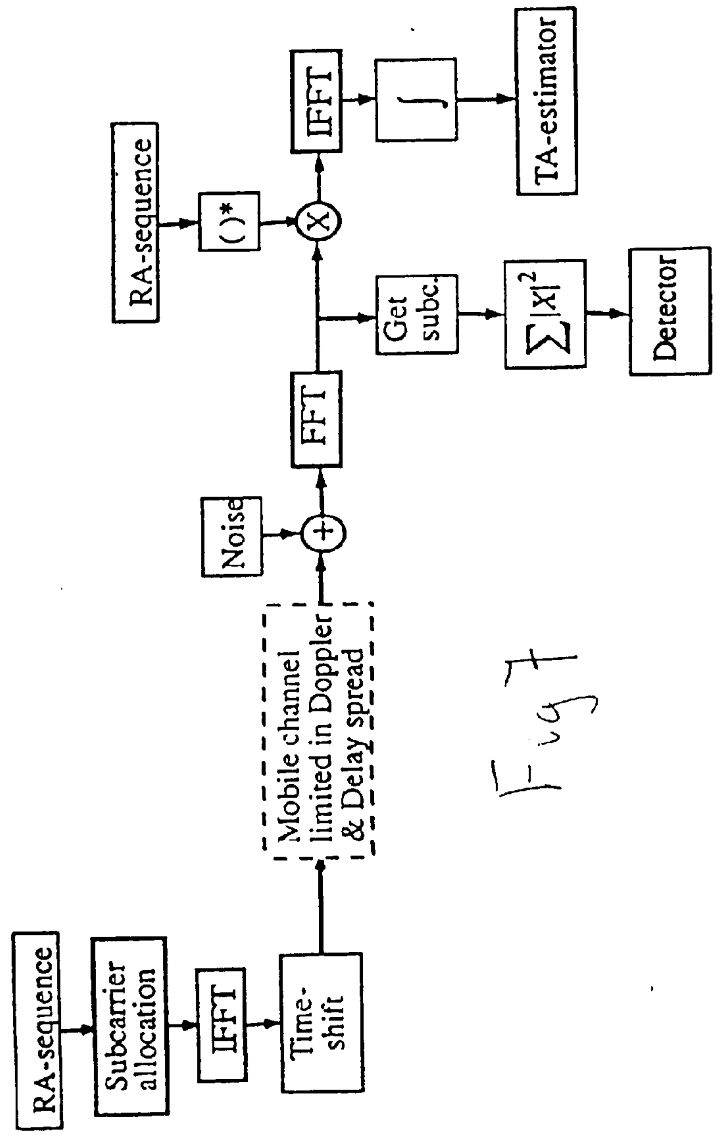

RA-sequence
Subcarrier allocation
IFFT
Time-shift
Mobile channel limited in Doppler & Delay spread
Noise
FFT
Get subc.
$\sum |X|^2$
Detector
RA-sequence
( )*
IFFT
TA-estimator

Fig 7

Fig 8

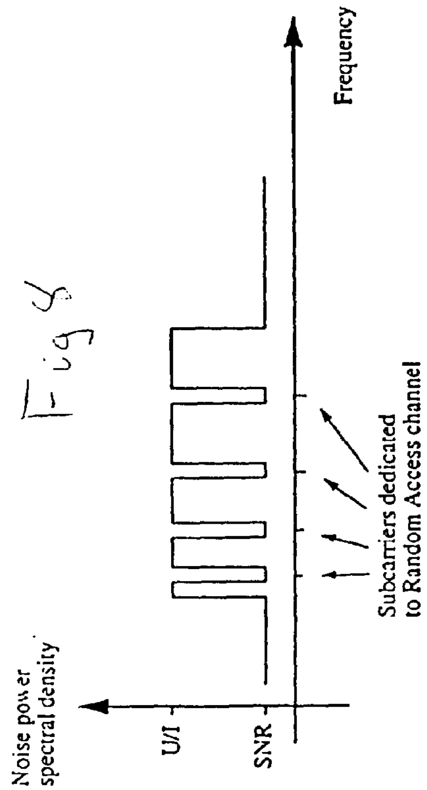


Fig 9

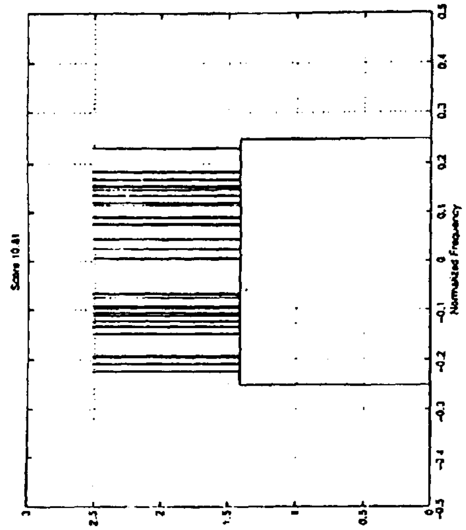


Fig 10

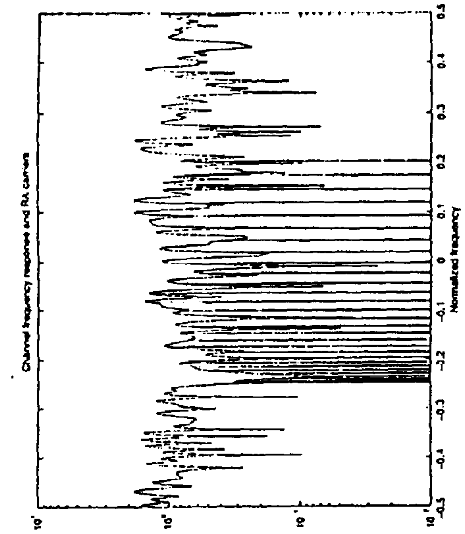


Fig 11

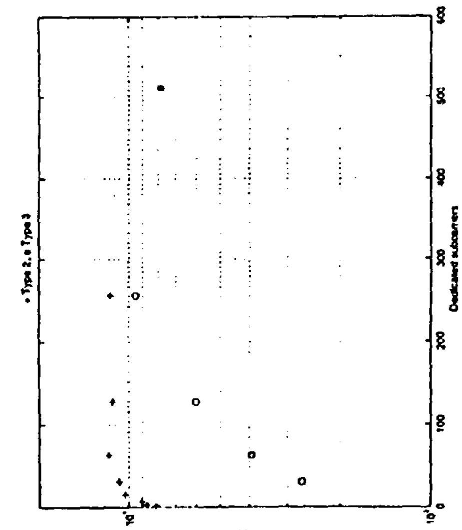
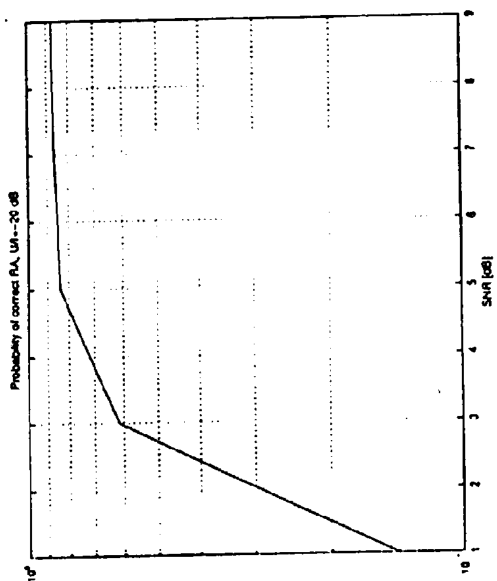


Fig 12



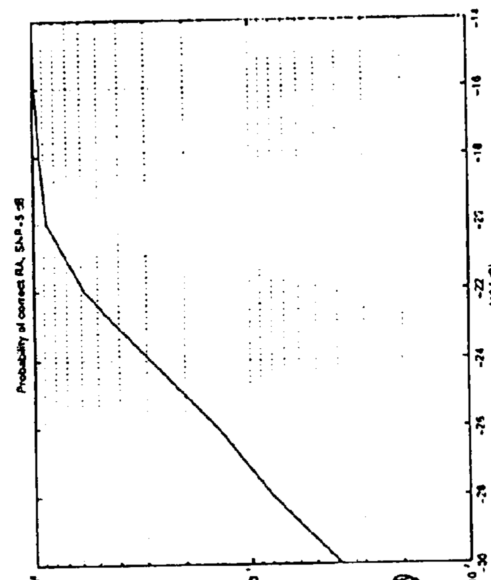
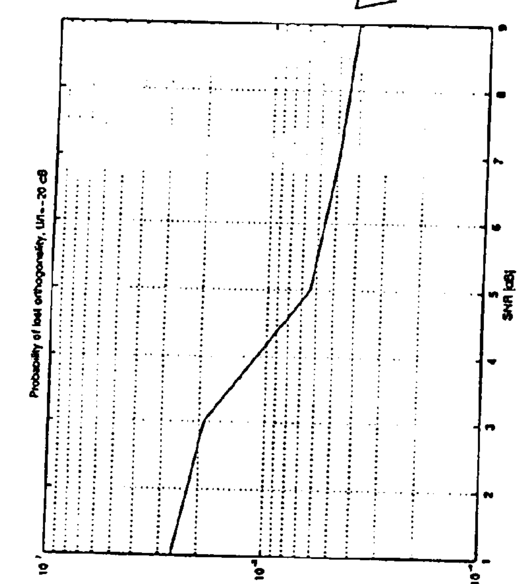


Fig 13

Fig 15



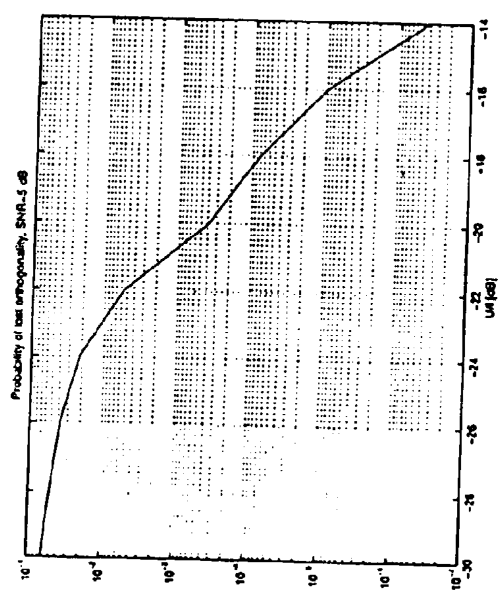


Fig 14